NASA TM-82761

NASA-TM-82761 19820008621

DOE/NASA/20305-7
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National Aeronautics and Space Administration
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Work performed for
U.S. DEPARTMENT OF ENERGY
Conservation and Renewable Energy
Division of Wind Energy Systems

Prepared for
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Conference and Workshop
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NOTICE

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Under Interagency Agreement DE-AI01-79ET20305

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N82-16495 #

E-1082

THE NASA LEWIS LARGE WIND TURBINE PROGRAM

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ABSTRACT

The large wind turbine program is a major segment of the Federal Wind Energy Program sponsored by the Department of Energy (DOE). The NASA Lewis Research Center manages the large wind turbine program for DOE. The large wind turbine program is directed toward development of the technology for safe, reliable, environmentally acceptable large wind turbines that have the potential to generate a significant amount of electricity at costs competitive with conventional electric generation systems. In addition, these large wind turbines must be fully compatible with electric utility operations and interface requirements.

There are several ongoing large wind system development projects directed toward meeting the technology requirements for utility applications. First generation technology machines (Mod-OA and Mod-1) and second generation machines (Mod-2) are in operation at selected utility sites. Third generation technology machines (Mod-5) are in the design phase and are scheduled for initial operation in 1984 if project funding is continued.

Each successive generation of technology has shown potential to increase reliability and energy capture, while reducing the cost-of-electricity. These advances are being made by gaining a better understanding of the system design drivers, improvements in the analytical design tools, verification of design methods with operating field data, and the incorporation of new technology and innovative designs.

This paper provides an overview of the large wind turbine program activities managed by NASA Lewis. These activities include results from the first and second generation field machines (Mod-OA, -1, and -2), the design phase of the third generation wind turbine (Mod-5) and the advanced technology projects. Also included is the status of the Department of Interior WTS-4 machine for which NASA is responsible for technical management.

INTRODUCTION

Since 1973, the United States Government has sponsored an expanding research and development program in wind energy in order to make wind turbines a viable technological alternative to existing electrical generating capacity. The current U.S. Wind Energy Program, under the sponsorship of the Department of Energy, is directed toward the development and production of safe, reliable, cost-effective machines which will generate significant amounts of electricity.

One element of the U.S. Wind Energy Program is Large Horizontal Axis Wind Turbine Development, which is being managed by the NASA Lewis Research Center. This activity consists of several ongoing wind system developments oriented primarily toward utility application. These projects are designated Mod-OA, Mod-1, Mod-2, WTS-4 and Mod-5. In addition to these machine projects there is a supporting research and development project that utilizes the Mod-0 wind turbine as an experimental test bed. These machine configurations are illustrated in Figure 1.

The machine design and technology development projects have been supported by substantial analysis and hardware/material testing. These include efforts to improve the methods of structural dynamic analysis, assessment of utility interface problems, testing of component materials, and evaluation of new blade concepts by analysis, laboratory testing of blade sections, and operational testing of full-scale blades. This paper presents an overview of the NASA wind turbine activities concentrating on the status of the major wind turbine development projects and the low cost blade activities.

LARGE WIND TURBINE DEVELOPMENTS

Mod-OA 200 kW Wind Turbine Project

The Mod-OA project was initiated in 1975 to obtain experience in operating large wind turbines on a utility grid. The Mod-0 100 kW machine was uprated to 200 kW, and the first installation was completed in 1977. Since then a machine has been installed each year at the sites shown in Fig. 2, with the last installation completed in July 1980. The machine has a (38m) 125 ft. diameter downwind full pitchable rotor, and is mounted on a (30m) 100 ft. rigid truss tower. The rated power is 200 kW at a wind speed of 18.1 mph (7.5 m/s).

The goals of the program were to demonstrate automatic operation, investigate compatibility with utilities, assess the reliability and maintenance requirements, and determine the public and utility reaction.

There were significant problems early in the program with reliability, and in particular rotor blade life. However, the machines have been upgraded with very significant results. The four machines have now accumulated 30,000 hours of operating time, and have generated 3,000 megawatt hours of energy. The availability of the machines often exceeds the goal of 90%, and for the last machine installed, averaged 80% for the first year.

The continuing machine operations at the four sites are providing very significant data for a wide variety of environment and wind conditions and utility situations (Reference 1). The operating experience has had a significant effect on the second and third generation machine designs.

Mod-1 2000 kW Wind Turbine Project

The Mod-1 project was initiated in 1974. The Mod-1 is a 2-bladed, 200-foot diameter wind turbine with a rated power of 2000 kW. The blades are steel and the rotor is located downwind of the tower. Full span pitch is used to

control the rotor speed at a constant 35 RPM. The gearbox and generator are similar in design to the Mod-0A but, of course, are much larger. The tower is a steel, tubular truss design. The General Electric Company, Space Division of Philadelphia, Pennsylvania is the prime contractor for designing, fabricating and installing the Mod-1. The Boeing Engineering & Construction Company of Seattle, Washington, manufactured the two steel blades. A single prototype was installed at Boone, North Carolina in May 1979 and began tests synchronized to the Blue Ridge Electrical Membership Corporation in September 1979 (Fig. 3). The Mod-1 has operated successfully in all modes of operation, synchronized in a fully automatic mode with the utility grid and furnished power directed to utility residential users within utility standards. This demonstrated the compatibility of a megawatt wind turbine operating into a utility grid in a stable and well controlled manner. In addition, data from machine testing has verified the performance, loads and structural dynamics codes used to design the MW size Mod-1. During Mod-1 operations at Boone there was also much testing done in support of nose and television interference (TVI) associated with the Mod-1 operating in a mountainous region (Ref. 2). The information from these tests is being factored into the design of the newer wind turbine developments.

To reduce rotor noise, the rotor speed and was reduced from 35 rpm to 23 rpm. This was accomplished by replacing the 2000 kW 1800 rpm generator with a 1500 kW 1200 rpm generator. Near the completion of the noise experiments, the Mod-1 experienced a failure in the low-speed shaft of the drive train. Since the Mod-1 has met most of its project goals and wind program funding has been reduced, it has not been decided to immediately repair the machine. The future of the Mod-1 is presently under evaluation to determine how it can best support the program.

Mod-2 2500 kW Wind Turbine Project

The Mod-2 wind turbine project is a second generation phase of the large wind turbine program managed by the NASA for DOE. DOE/NASA awarded the contract to design and build a second generation, Mod-2 wind turbine in August 1977. The specific objective of the Mod-2 project is to establish the design and performance of a megawatt-size wind turbine that can achieve a cost-of-energy for the 100th unit in production of less than 5¢/kWh including capital, and operating and maintenance costs, in 1980 dollars. For purposes of estimating COE, the wind turbines are assumed to be deployed in a twenty-five unit cluster at a site having an annual mean wind speed of 6.3 m/s (14 mph) at a height of 9.1 m (Fig. 4). The installation of three Mod-2 machines clustered at a single site at Goldendale, Washington, is expected to test, evaluate and demonstrate the interactive aerodynamic and electrical grid effects of multiple machines integrated into a utility network.

The DOE selected the Bonneville Power Administration (BPA) as the participating utility of the Mod-2 wind turbine project. This utility was selected for the reasons of its scope as a large regional power-distributing organization in the Pacific Northwest and its capability of supplying valuable support in attainment of the DOE/NASA project goals.

The Mod-2 project is now in the experimental operations phase which offers a unique opportunity to study the effects of single and multiple wind turbines interacting with each other, the power grid, and the environment during the next two years. To date, initial performance of the turbines has been acceptable but also has indicated areas for optimization. Corrective actions have been taken to modify the turbines as necessitated by the June 8, 1981 failure of turbine No. 1's safety system. Test operations are expected to be resumed in early Fall on turbine No. 2 and No. 3. Full three machine cluster operation is anticipated in early CY 82 (Ref. 3).

WTS-4 4000 kW Wind Turbine Project

LeRC is participating in a joint project with the Department of the Interior (DOI) Bureau of Reclamation to install two megawatt-size system verification units (SVU) wind turbines near Medicine Bow, Wyoming. Operation of the SVU's is expected to verify the concept of integrating wind turbines and hydroelectric facilities as a key step in Relamation's long range program to supplement their hydro power generation with extensive wind turbine capacity.

The Hamilton Standard Division of United Technologies Corporation was selected by competitive procurement to design, fabricate, install and test a 4-megawatt WTS-4 machine (Fig. 5). A Swedish company, Karlskronavarvet (KKRV), is a major subcontractor responsible for the design and fabrication of the nacelle hardware. A 3-megawatt version of the same basic design is being built for the Swedish government with KKRV as the prime and Hamilton Standard as the major subcontractor. The second SVU is a 2.5-megawatt Mod-2 of the same design as the Goodnoe Hills machines.

Currently the WTS-4 nacelle is in final factory checkout testing prior to being shipped from Sweden to Medicine Bow in December 1981. It is scheduled to arrive in Medicine Bow in February 1982 when it will be rechecked before being installed on the tower which will be erected in October this year. The two single piece filament wound fiberglass blades are currently being fabricated at the dedicated Hamilton Standard winding facility in East Granby, Connecticut. They will be trucked to Medicine Bow and installed on the WTS-4 prior to nacelle erection. Two identical blades have already been completed and shipped to Sweden. First rotation of the WTS-4 is scheduled for June of 1982 (Ref. 4).

Mod-5A Advanced Multi-MW Wind Turbine Project

The Mod-5A advance design wind turbine is being developed for DOE/NASA by the General Electric Company's, Advanced Energy Programs Department. Work on the project was initiated in July 1980. The conceptual design was completed in March 1981; preliminary design is currently in progress with completion scheduled for March 1982. It is anticipated that the design will be complete and fabrication initiated early in 1983. Machine operation is expected by the Fall of 1984.

The primary requirement of this project is to develop a multi-megawatt wind turbine generator that produces electricity for less than 3.75¢/kWh (1980 dollars) when installed as a cluster of 30 machines at a site with a 14 mph

average wind speed. During the conceptual design phase many trade studies were performed to establish the size and configuration that would produce the lowest cost of energy. The major trade studies performed included: blade materials, fiberglass vs. steel vs. wood epoxy; blade articulation, independently coned vs. teetered; orientation, upwind vs. downwind; torque control, flaps vs. partial span control; tower height; system rpm, single speed vs. multi-speed; gearbox/nacelle configuration, separate gearboxes integral gearbox vs. rotor integrated gearbox and size, and both rotor diameter and rated power.

The conceptual design effort produced a wind turbine design with a projected 100th unit cost of energy of just under 3¢/kWh (Ref. 5). The wind turbine has a 400 ft. diameter wood epoxy rotor mounted directly on the gearbox. The two speed gearbox drives a 6.2 MW synchronous generator. The soft tubular tower provides a rotor centerline 250 ft. above ground level. Figure 6 shows an artists concept of the machine.

Mod-5B Advanced Multi-MW Wind Turbine Project

The Mod-5B advance design wind turbine is also being developed by the Boeing Engineering & Construction Company for DOE/NASA. Work started in July 1980. The conceptual design is completed and the preliminary design is in progress and scheduled to be completed in February 1982. The Mod-5B wind turbine is being designed to produce electricity for utilities at the lowest practical cost (3.75¢/kWh, 1980 dollars) in a wide variety of locations which need to have only moderate (14 mph) average annual wind speeds. It is based on the technology developed on the previous Mod-2 wind turbine program, but it has roughly twice the rotor area (420 ft. diameter vs. 300 ft.) and almost three times the power (7.2 MW vs. 2.5 MW) compared to the Mod-2 (Fig. 7). Advanced technology is featured in rotating light weight wood blade tips, and variable rotor speed operation to extract the maximum power at different wind speeds. Proven concepts such as a teetering rotor supported from the drive shaft by elastomeric bearings, a low cost epicyclic speed increasing gearbox, and rotor speed control employing only the variable pitch blade tips are retained from the Mod-2 (Ref. 6).

This project has recently completed the concept design stage and is now in preliminary design. The detailed design is scheduled for completion in late 1982 and erection and operation at a site, to be determined, should take place in early 1984 subject to continued program funding.

Summary of Large Wind Turbine Developments

Much understanding and progress has been made in designing more efficient, lighter weight, and lower cost wind turbines since the first Mod-OA started operations in 1977 at Clayton, New Mexico. Figure 8 shows the first rotation dates for each of the large wind turbines. A brief summary of progress to date for large machines is outlined in Figure 9. Figure 9 compares key factors for large wind turbines such as $/kW & kWh/lb for the first, second and third generation machines. The Mod-OA is used for first generation, Mod-2 for second generation and Mod-5 for third generation. All numerical values in Figure 9 are for the second prototype machine of each generation. As can be seen in the figure, there is a major reduction in $/kW from Mod-OA to Mod-2

with an additional 20% reduction from Mod-2 to Mod-5. It is interesting to note that the kWh/lb, which is an indirect measure of revenue to cost, increases with each generation with a doubling occurring from first to third. This is impressive considering it means doubling the energy output for the same weight or maintaining equal energy out with a machine at half the weight. It is even more important considering the Mod-OA was a fairly lightweight machine and utilized aircraft quality lightweight aluminum blades. These gains were made by utilizing advanced technology such as teetered rotors, tip-controlled blades, epicyclic gearboxes, towers with lower natural frequencies, rotors made with significantly lower cost materials and methods and improved analysis tools and increased understanding of the major design devices. It is also interesting to note in Figure 9 how the percentage of $/kW for major subsystems has changed from Mod-OA to Mod-5 with the rotor now being a much smaller percentage of the machine cost.

WIND TURBINE TECHNOLOGY DEVELOPMENT

Wind turbine technology development is carried on under a supporting research and technology project. Two primary areas of technology development consist of the key component/system experiments performed on the Mod-0 test bed machine and the development of improved lower cost components such as rotor blades. This paper briefly describes the role of the Mod-0 machine and the low-cost long-life rotor blade developments.

Mod-0 Experimental Test-Bed

The Mod-0 wind turbine was designed and built as an experimental test-bed and began operations in September 1975. The machine has been modified extensively to keep pace with the technology developments of the large horizontal-axis wind turbines (Fig. 10). The Mod-0 was originally erected as a first-generation downwind, full span pitch control, rigid rotor and stiff (more than 2P) tower. In the first generation configuration the Mod-0 was instrumental in: (1) verifying the early aerodynamic, structural and electrical performance codes for WT design and; (2) providing the design tools and operating experience needed for the development of the first generation Mod-OAs and Mod-1.

As the second generation Mod-2 concept entered design, the Mod-0 was modified to test tip-controlled blades, teetering rotors, more flexible towers, and upwind/downwind rotors. To support the newer third generation developments the Mod-0 is being re-configured to test teetering/delta-3 rotors passive yaw, variable speed drive trains and more flexible towers (less than 1P). The Mod-0 has proven to be a very effective facility for evaluating and verifying new configurations, components, control strategies etc. for the advanced horizontal-axis wind turbine developments.

Rotor Blade Developments

Aluminum Blade Development

Nine aluminum blades were built by Lockheed Aircraft Corporation in support of the early wind turbine projects. Three blades were built for the Mod-0 and

six for the first three Mod-OAs. These blades were of typical spar stringer construction used for aircraft wings. These early blades were very important in providing rotors that allowed overall testing of the early machines. However, the aluminum blades were judged to be too expensive for future cost-effective wind turbines and did not show sufficient promise for reduced cost to justify additional development. At the present time, all the aluminum blades have been replaced with later developed wood composite, fiberglass and steel blades. Again, the aluminum blades played a very important role in the early wind turbine projects, as they were the only blades available at the start of program.

Early Fiberglass Blade Development

From the start of the large wind turbine program in 1974, fiberglass composites were considered prime condidates for wind turbine blades. Fiberglass and epoxy or polyester composites have properties which are desirable for WT blades: high strength to weight ratio, good fatigue strength, tolerance to structural defects, high resistance to environmental factors, properties which remain constant with time, readily fabricated into large structures, and reasonable cost per lb. in production. These properties have resulted in fiberglass replacing wood and metal in boats up to almost 100 feet and in replacing metal in large tanks, pressure vessels, and pipes.

The first fiberglass blade project utilized filament wound fiberglass technology and was designed and built by a joint Hamilton-Standard and ABL, Inc. effort. Hamilton-Standard designed the blade using design tools developed for propeller design. ABL designed the filament winding process and equipment based on their pressure vessel and rocket nozzle winding experience. A 60 foot blade for the 200 kW Mod-OA was designed, fabricated and static tested (Fig. 11). The blade met all of the design requirements.

The second fiberglass blade project was intended to develop a technique for fabricating large blades (150 feet) and to demonstrate the applicability of the fiberglass tape winding process which is being used to fabricate pipe (Fig. 12). The project was a joint venture with Kaman Aerospace and SCI Corporation. Kaman designed the blade using analysis tools developed for helicopter blades and SCI designed the tape winding process and equipment based on their tank and pipe winding experience. The 150 foot "D" spar was wound at SCI's facility in California and shipped to Kaman's facility in Conn. Kaman completed the blade by bonding prefabricated top and bottom aft panels to the spar and installing a steel adapter in the root end of the blade to connect to the WT hub. The blade was static tested and failed at 106% of design limit load. The failed section was examined and found to have a fabrication fault. The out-board 100 foot of the blade did not have this fault and was tested separately to about 200% of design limit load without failure.

Current Fiberglass Composite Blade Development

Four companies now have the capability to fabricate large fiberglass composite blades. Each company received government support on previous blade contracts and some continued the development effort on company funds. SCI completed

fabrication of two tape wound 60 foot blades which are operating on the 200 kW Mod-OA WT in Clayton, New Mexico (Fig. 13). Kaman Aerospace completed fabrication of two 32 foot tape wound blades which are operating on their 40 kW wind turbine at Rocky Flats, Colordado. Kaman also completed fabrication of two 100 foot tape wound blades for the Mod-1 WT (Fig. 14). ABL, using company funding, has designed a blade and fabricated the blade assembly equipment. They now have the capability to design and fabricate a blade although they have not yet built their first blade. Hamilton Standard has completed fabrication of two 127 foot filament wound blades for Sweden and is currenty fabricating two more blades for the Bureau of Reclamation for the SVU project (Fig. 15).

The Kaman 100 foot blade is a direct application of the technology from the 150 foot blade program. The spar is tape wound and top and bottom aft panels are prefabricated and bonded to the spar with a chordwise tape wrap over the butt joint between adjacent panels.

The Kaman 32 foot blades and the SCI 60 foot blades are different from the 150 foot blade primarily in the way the aft panels are fabricated. Both have a tape wound "D" spar to which foam mandrels are bonded to form the aft panel contour. The combined "D" spar and foam mandrels are then wrapped with fiberglass tape. The interface between the fiberglass blade and the steel fitting which connects to the hub is a key design area. Fatigue tests of this joint are conducted on all blades in the DOE/NASA 60 foot blade development program. The SCI blade was part of this program and the fatigue test of half scale root ends indicated the capability of the root end exceeded design requirements.

The Hamilton Standard Company fabricates the 127 foot filament wound blade by first winding a "D" spar on a removable mandrel, then securing a removable aft mandrel to the "D" spar and winding over the combined "D" spar and aft mandrels. The winding process is highly automated. Both the angle of the glass fibers and the thickness at each section are controlled by a computer.

Wood Epoxy Composite Blade Development

The Government funded Gougeon Brothers to develop a 60 foot wood epoxy composite blade using their wood epoxy saturation technique (WEST) process. The blades are built by laying up fiberglass, epoxy, and 1/16 to 0.10 inch thick wood veneers in molds of the top and bottom half of the blade. The top and bottom interface surfaces are sawed square and bonded together with epoxy. Tapered steel studs are epoxy bonded into the root end to attach the blade to the hub.

Using this technique eight 60 foot blades have been built for use on the Mod-OA wind turbines (Fig. 16). Three Mod-OA wind turbines presently have wood blades and have operated for approximately seven, five, and one thousand hours. This blade development has been supported by small scale fatigue tests and by fatigue tests of the full scale wood to stud to hub joint.

The wood blade technology has been applied to both smaller and larger blades. Blades 25.5, 21.5, and 10 feet long have been built and tested on wind

turbines and Gougeon has the commercial order for these blades. The wood blade was a candidate for the 400 foot Mod-5A and Mod-5B rotors. Boeing and G.E. conducted trade-off studies between steel, fiberglass and wood for rotors. Boeing selected wood composite for the movable tip provided the strength of the stud to wood joint could be increased. GE selected wood composite for an all wood rotor.

Steel Blade Development

The government has supported the development of large steel blades at LeRC, Boeing and The Budd Company (Fig. 17). In addition to these programs, WTG, Inc. has developed a 40 foot blade for the WTG 200 kW wind turbine using company funds. LeRC and Budd have developed 60 foot blades and Boeing has developed a 100 foot blade for Mod-1 and a 300 foot steel rotor for Mod-2.

The WTG 40 foot blades are constant chord and use steel pipe with a flange welded on the end as the primary load carrying member. The airfoil structure is formed by welding ribs to the steel pipe and then covering the ribs with aluminum or steel sheet.

The LeRC 60 foot blade uses a round tapered steel utility pole with a flange welded on the end as the primary structural member. The airfoil section is formed by epoxying wood ribs to the spar and covering the ribs with a fine mesh fiberglass cloth. This cloth comes coated with a material which causes the cloth to shrink when sprayed with dope as with traditional fabric covered aircraft surfaces. The life of the airfoil surface is similar to that for other fiberglass structures.

The Boeing Engineering and Constructin Company (BEC) has designed and constructed two 100 foot blades for the Mod-1 WT and four 300 foot rotors for the Mod-2 WTs.

Blade Fatigue Testing

A key technology area of blade development is design and verification of blade life for thirty years. To verify this life the key design driver loads such as the hurricane winds, high wind shutdowns, emergency shutdown, rated power operations etc. are identified. In most blade designs the key interface is where the blade attaches to the rotor hub. Figure 18 shows results of a typical blade specimen tested for fatigue similar to tests run on helicopter blades. The full size blade specimen (normally just 20 feet from the hub out) is loaded and operated for various design load cycles. This technique has successfully identified structural "hot-spots" and been used to qualify the blades for long-life.

Summary of Blade Developments

The dollars per pound versus blade length is shown in Figure 19 for many of the large wind turbine blade developments. The data shown in this figure is based on the assumption that the blades are the 100th blade of a 100 blade production run. The data in Figure 19 is based on estimates, but in all cases hardware has been built. There are two major points to be made from the

Figure 19: (1) there has been a dramatic improvement in blade costs over the very early aluminum blades; and (2) there is a definite economy in scale in terms of dollars per pound for the larger blades. The reduction in blade costs coupled with the development of qualification testing of blades has resulted in several very promising blade designs/materials to support future wind turbines (Ref. 7). The rotor blades are no longer a key technology barrier to the development of cost effective large wind turbines.

CONCLUDING REMARKS

The large wind turbine portion of the Federal Wind Energy Program is managed by NASA Lewis Research Center for the Department of Energy (DOE). This portion of the program consists of several large wind turbine development projects and a supporting research and technology project (SR&T). A summary of the progress and status of these second projects follows:

1. Four Mod-OA 200 kW wind turbines have now operated over 30,000 hours and generated 3000 megawatt hours of electricity on utility systems. The Westinghouse Corporation under contract to NASA Lewis is primarily responsible for regularly reporting on performance of these machines and for providing any necessary servicing over and above routine maintenance.

2. The 2000 kW Mod-1 wind turbine, designed and built by the General Electric Corporation, successfully validated the analysis methods for predicting power, loads and dynamics for a large MW wind turbine. This validation was important for the follow-on development of the advanced large wind turbines. In addition, key environmental experiments on television interference and rotor noise were conducted and the results factored into the advanced wind turbine designs.

3. The three 2500 kW Mod-2s designed and built by Boeing Engineering & Construction Company, have been built and installed on the Bonneville Power Administration system and accepance testing is in progress. An overspeed incident on one machine caused some damage, but the problem has been corrected and all three machines will be back in operation by the end of 1981. Prior to the overspeed incident, performance of the Mod-2 wind turbines was very good and there appears to be no major design problems.

4. The Bureau of Reclamation has a 2500 kW Mod-2 and a 4000 kW WTS-4 wind turbine in fabrication and construction for operations at their Medicine Bow site in Wyoming. The WTS-4 wind turbine is being designed and built by Hamilton Standard. NASA has technical management responsibility for both wind turbines. Boeing will furnish the Mod-2 machine.

5. Two contractors, General Electric and Boeing, are each designing third generation large wind turbines designated Mod-5. Both machine designs show potential for significant cost reduction over the early machines. These estimated cost reductions are due primarily to larger size (6 to 7 MW with rotor diameters of 400 feet or more) and utilization of advanced technology such as variable speed generators and wood composite rotors.

6. The Mod-0 test bed continues to be used extensively to support key technology experiments in support of the advanced wind turbine designs. Most recent experiments include free-yaw, delta-3 teetered rotor, multi-speed operation, fixed pitch operations etc. Major progress has also been made in the Supporting Research and Technology (SR&T) project in developing rotor blades with potential for long-life and low-cost. Other SR&T projcts include variable speed generator technology and continued improvements in key performance and structural dynamics tools.

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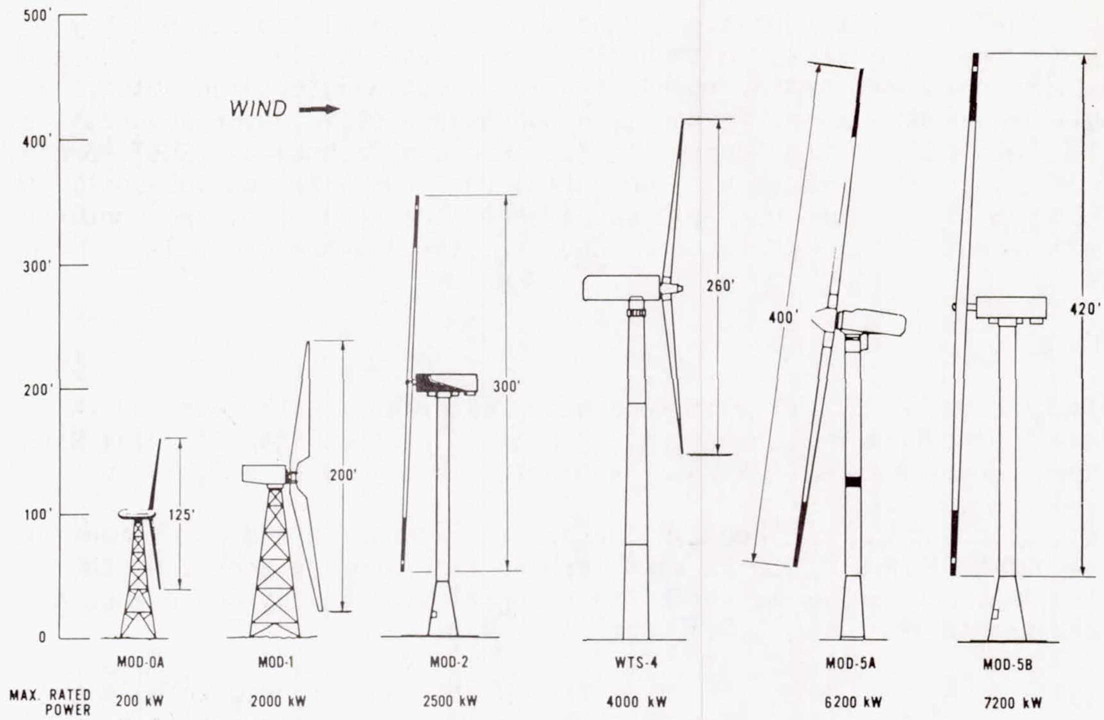
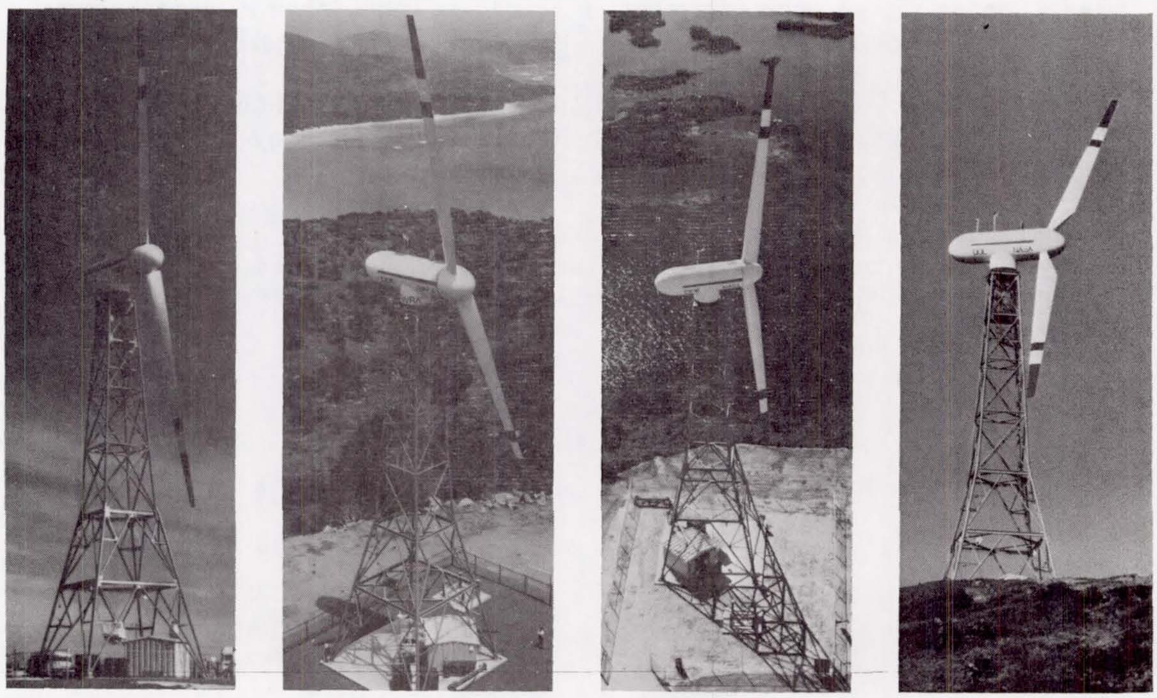


Figure 1. - Large horizontal axis wind turbines.



CLAYTON, NEW MEXICO **CULEBRA, PUERTO RICO** **BLOCK ISLAND, RHODE ISLAND** **KAHUKU PT., OAHU, HAWAII**

Figure 2. - Mod-0A 200 kW wind turbines.

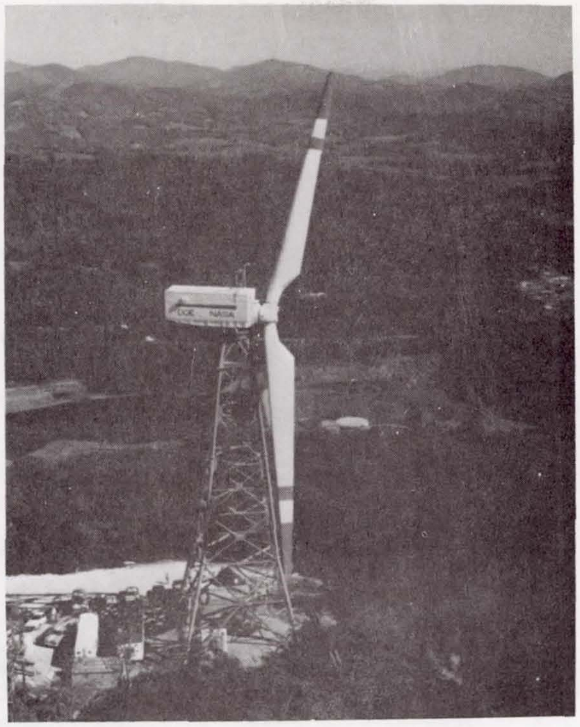


Figure 3. - Mod-1 2000 kW wind turbine.

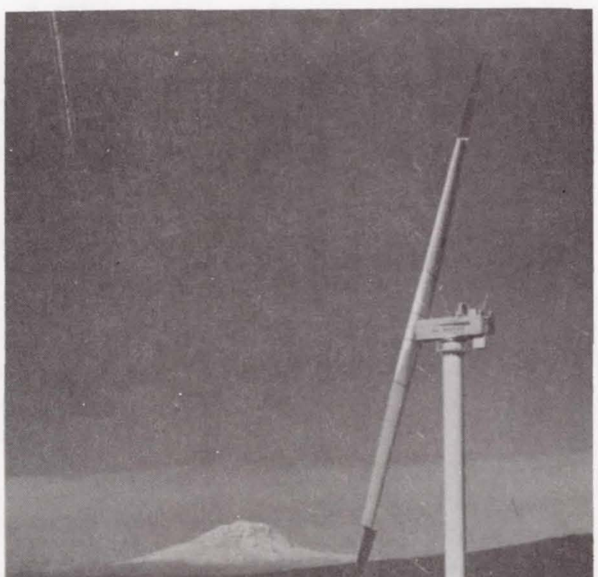


Figure 4. - Mod-2 2500 kW wind turbine.

Figure 5. - WTS-4 4000 kW wind turbine.

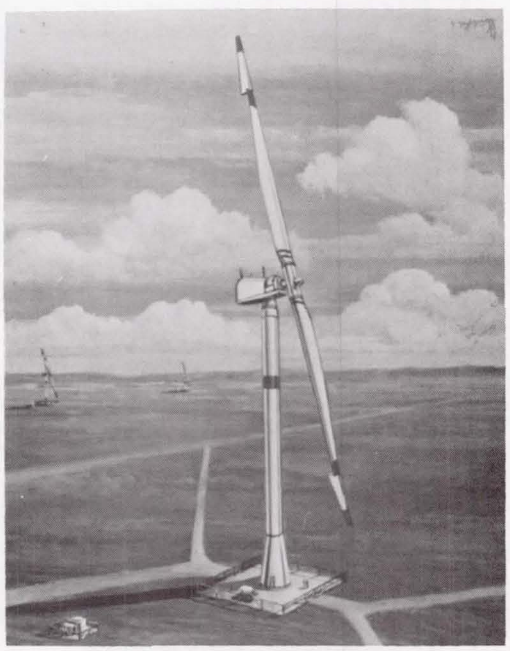


Figure 6. - Mod-5A 6000 kW wind turbine.

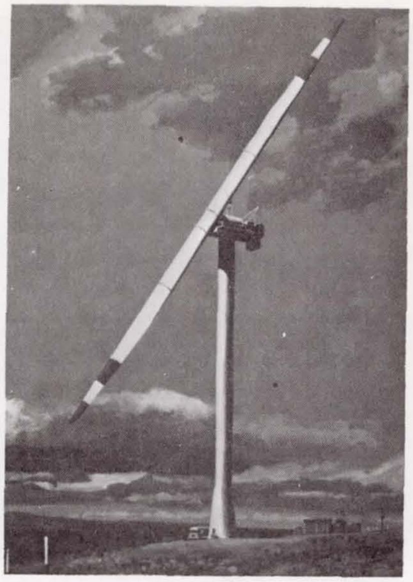


Figure 7. - Mod-5B 7200 kW wind turbine.

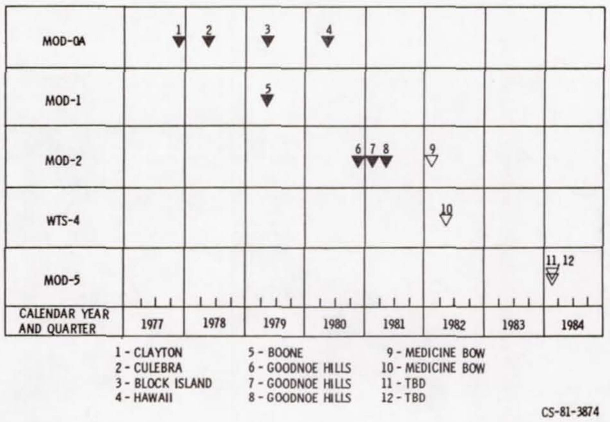


Figure 8. - Schedule of first rotation dates for large wind turbines.

COMPARISON OF LARGE WIND TURBINE DESIGNS*

GENERATION	FIRST	SECOND	THIRD
WIND TURBINE	MOD-0A	MOD-2	MOD-5
COST ($/kW)	10,000	1700	1300
COMPONENT COST (% OF TOTAL)	ROTOR, SHIP & INSTALL, POD, TOWER	SHIP & INSTALL, ROTOR, POD	SHIP & INSTALL, ROTOR, TOWER, POD
DESIGN EFFICIENCY (kWh/lb)	9	15	18

* BASED ON SECOND UNIT PROTOTYPE COSTS

Figure 9. - Key factors for large wind turbines.

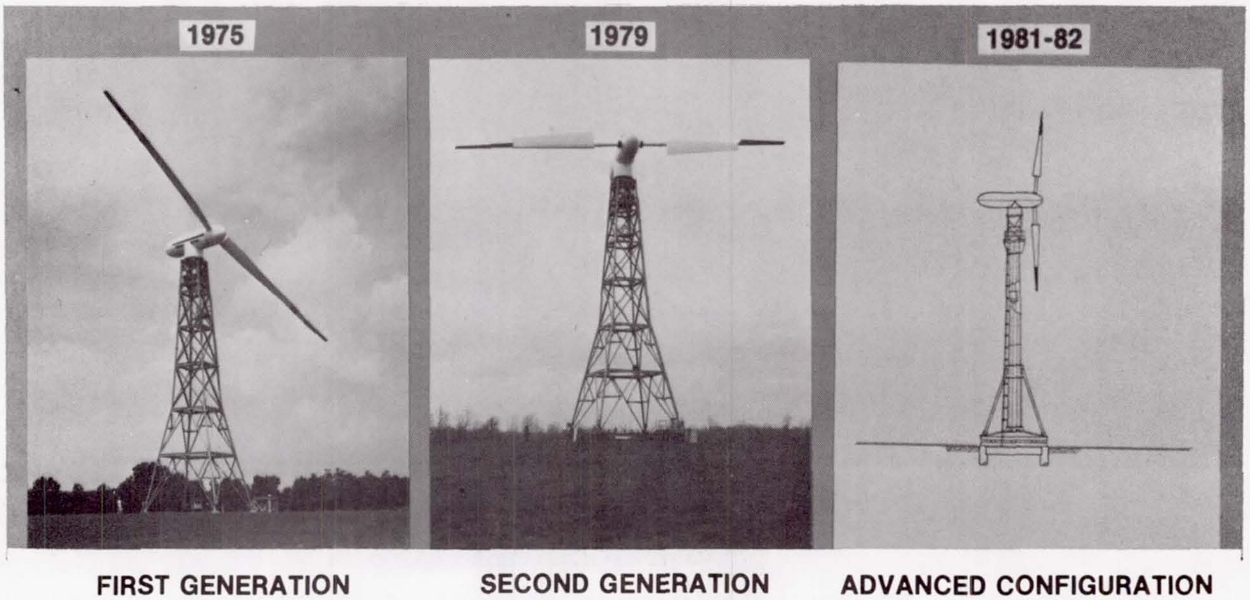


Figure 10. - Mod-0 wind turbine experimental test configurations.

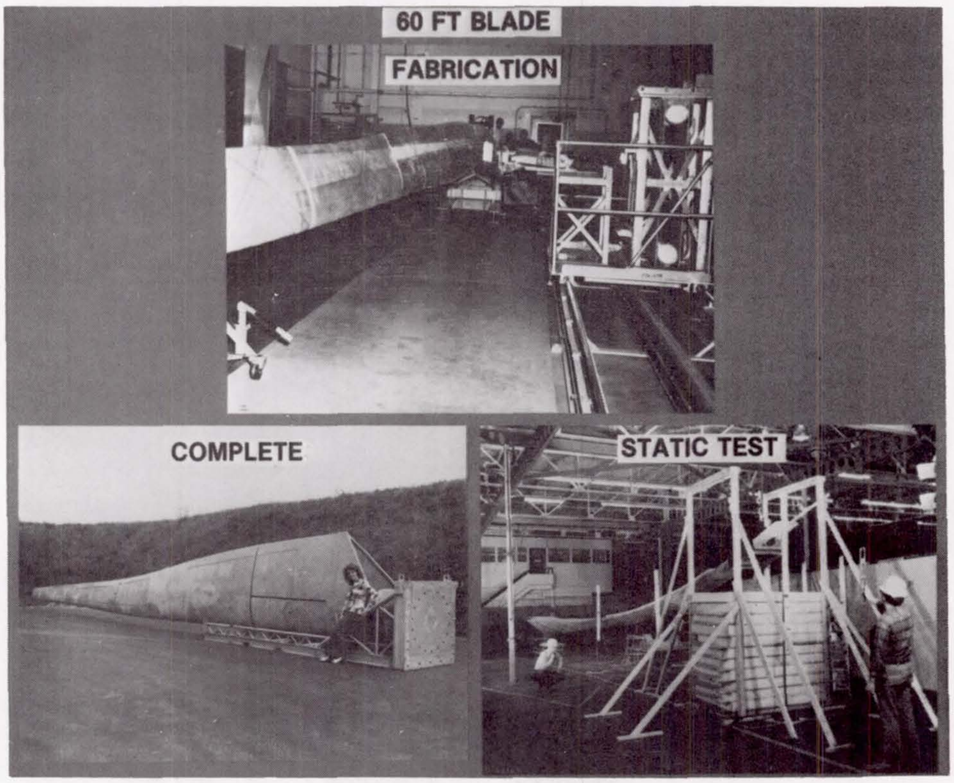


Figure 11. - Early hamilton standard 60 ft fiberglass blade.

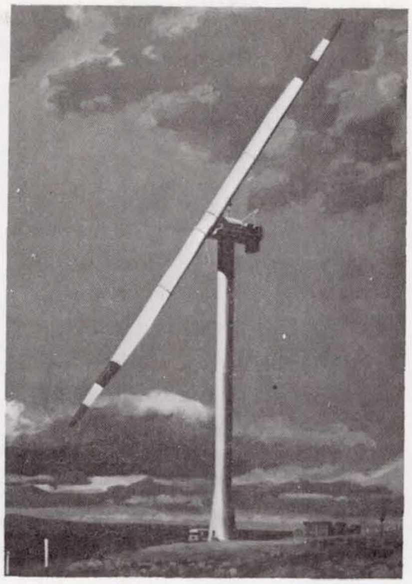


Figure 7. - Mod-5B 7200 kW wind turbine.

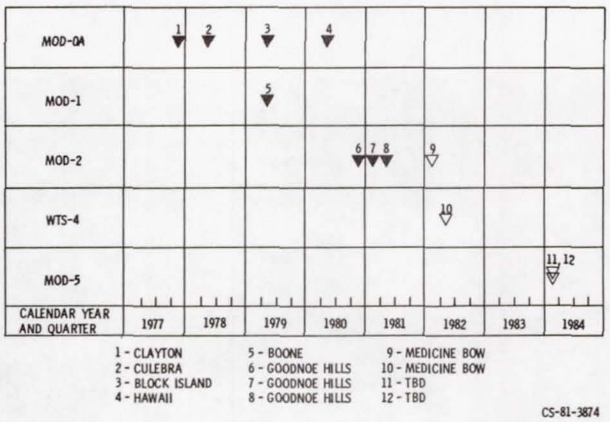
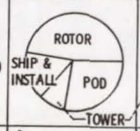
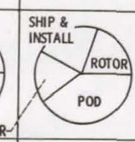
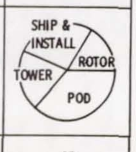


Figure 8. - Schedule of first rotation dates for large wind turbines.

COMPARISON OF LARGE WIND TURBINE DESIGNS*

GENERATION	FIRST	SECOND	THIRD
WIND TURBINE	MOD-0A	MOD-2	MOD-5
COST ($/kW)	10,000	1700	1300
COMPONENT COST (% OF TOTAL)			
DESIGN EFFICIENCY (kWh/lb)	9	15	18

* BASED ON SECOND UNIT PROTOTYPE COSTS

Figure 9. - Key factors for large wind turbines.

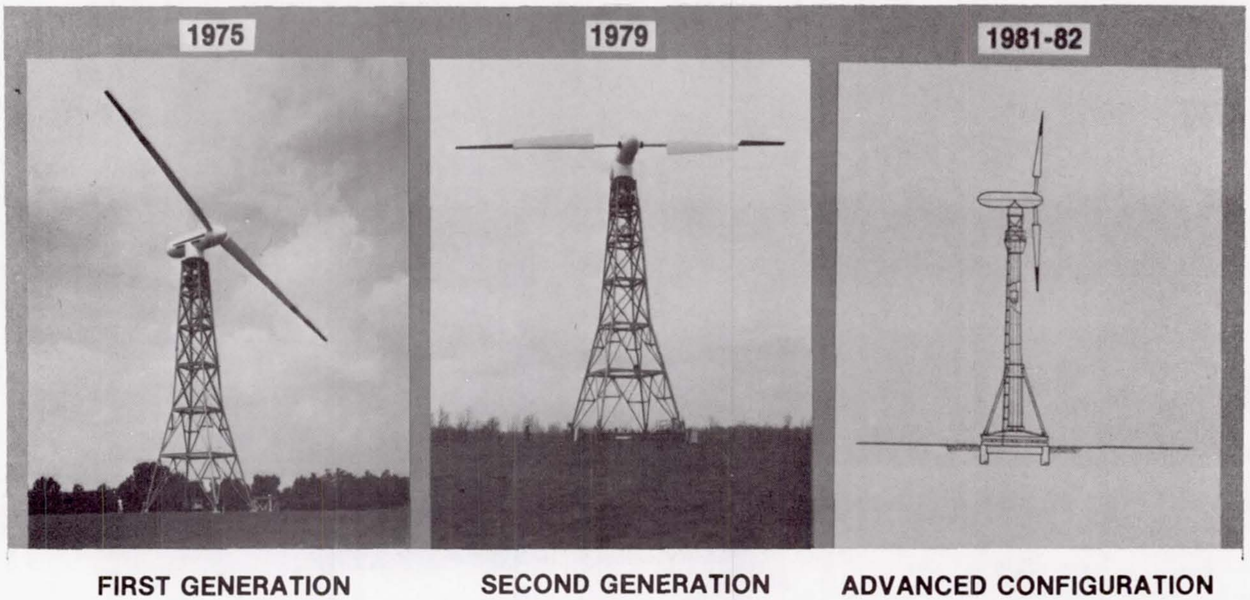


Figure 10. - Mod-0 wind turbine experimental test configurations.

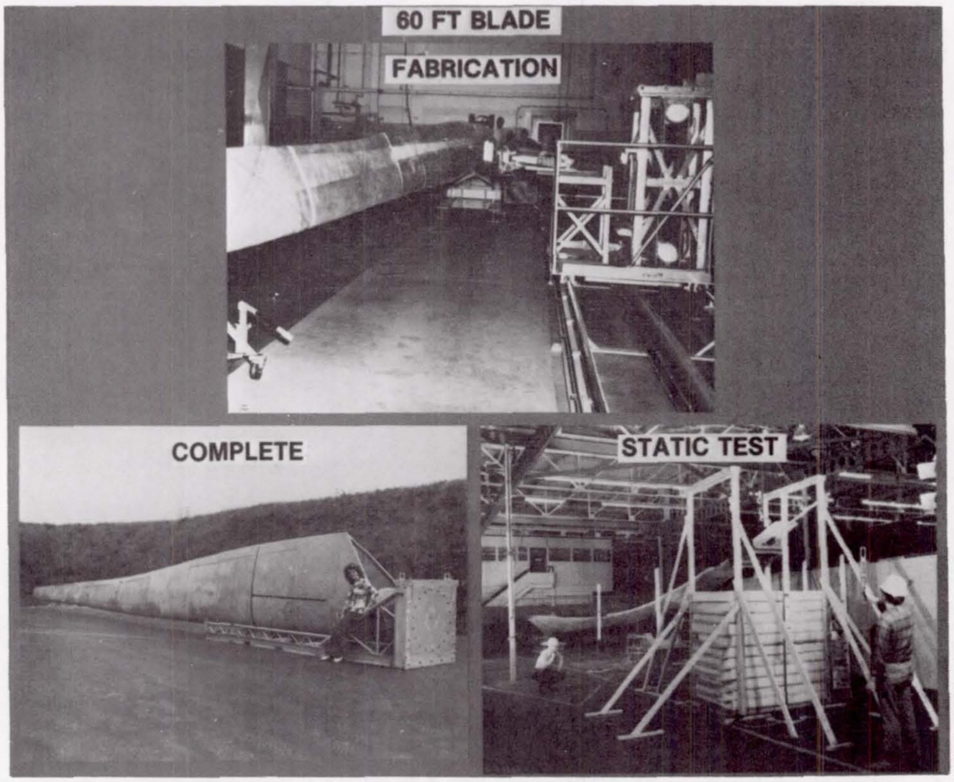


Figure 11. - Early hamilton standard 60 ft fiberglass blade.

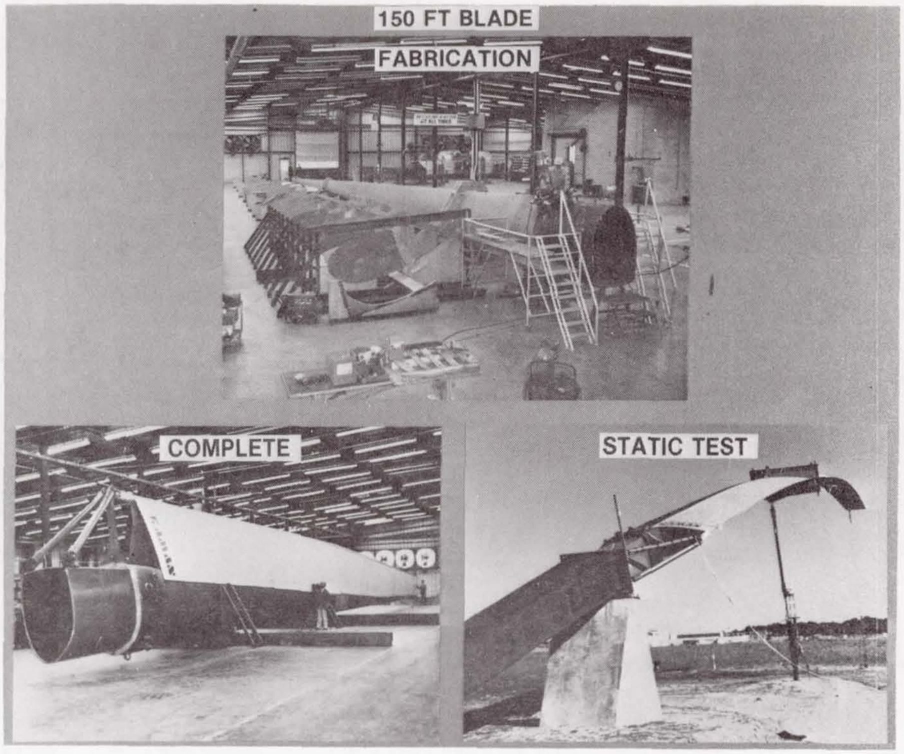


Figure 12. - Kaman/SCI 150 ft fiberglass blade.

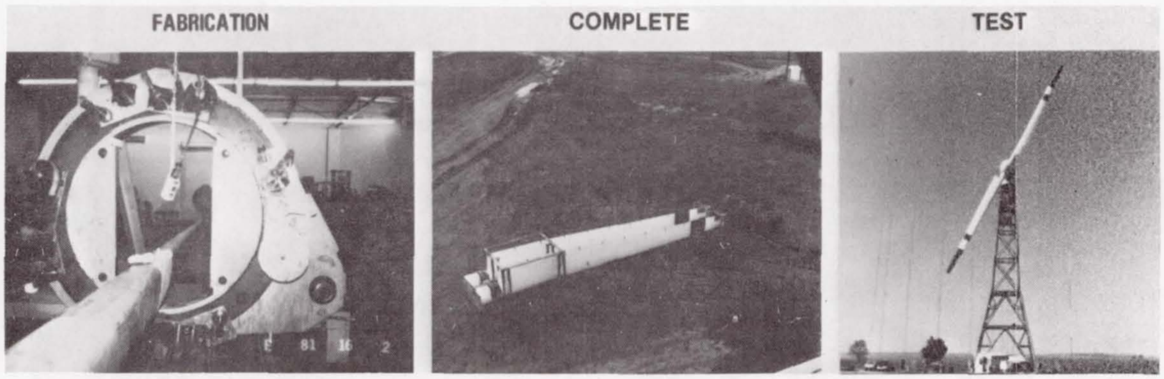


Figure 13. - SCI blade 60 ft Mod-0A.

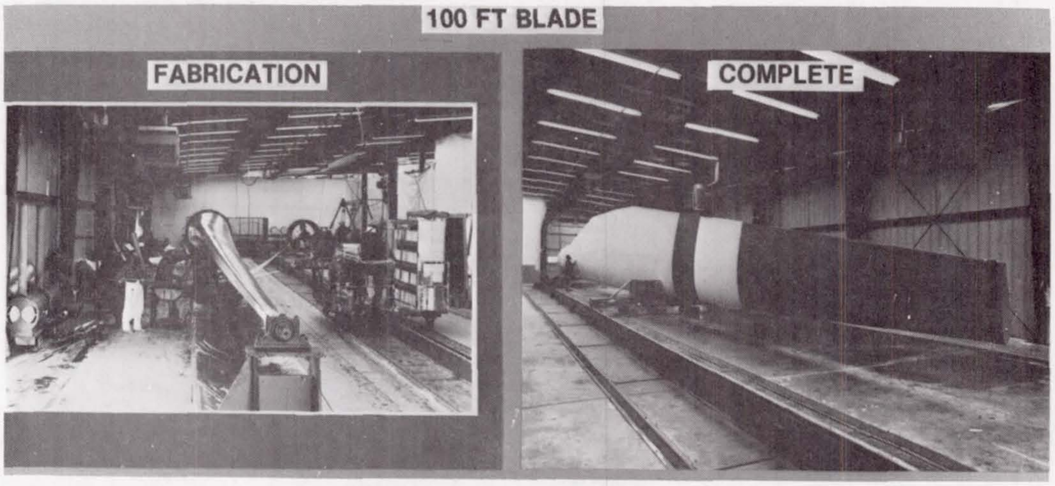


Figure 14. - Kaman 100 ft Mod-1 blades.

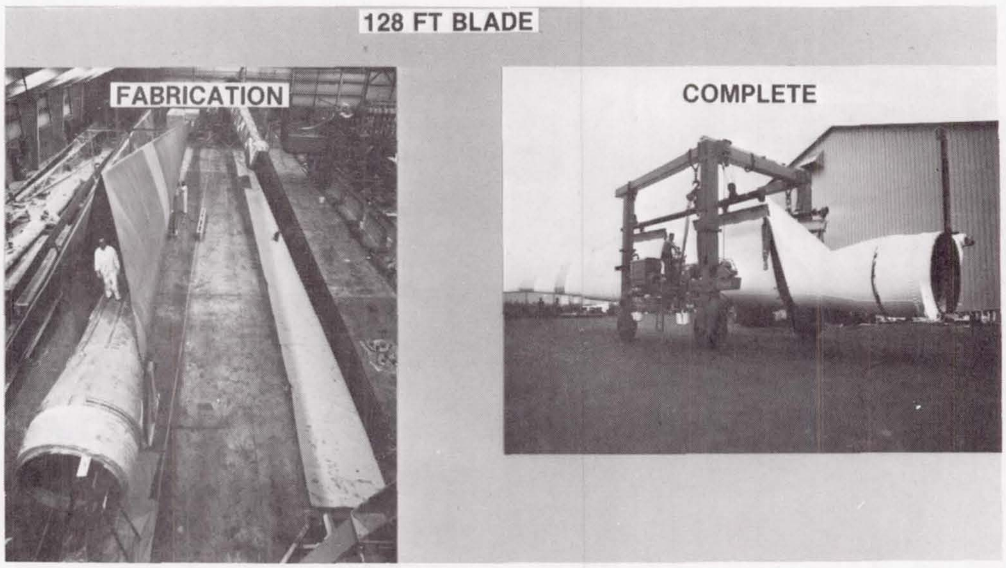


Figure 15. - Hamilton standard 128 ft WTS-4 fiberglass blades.

Figure 16. - Gougeon laminated wood composite blades.

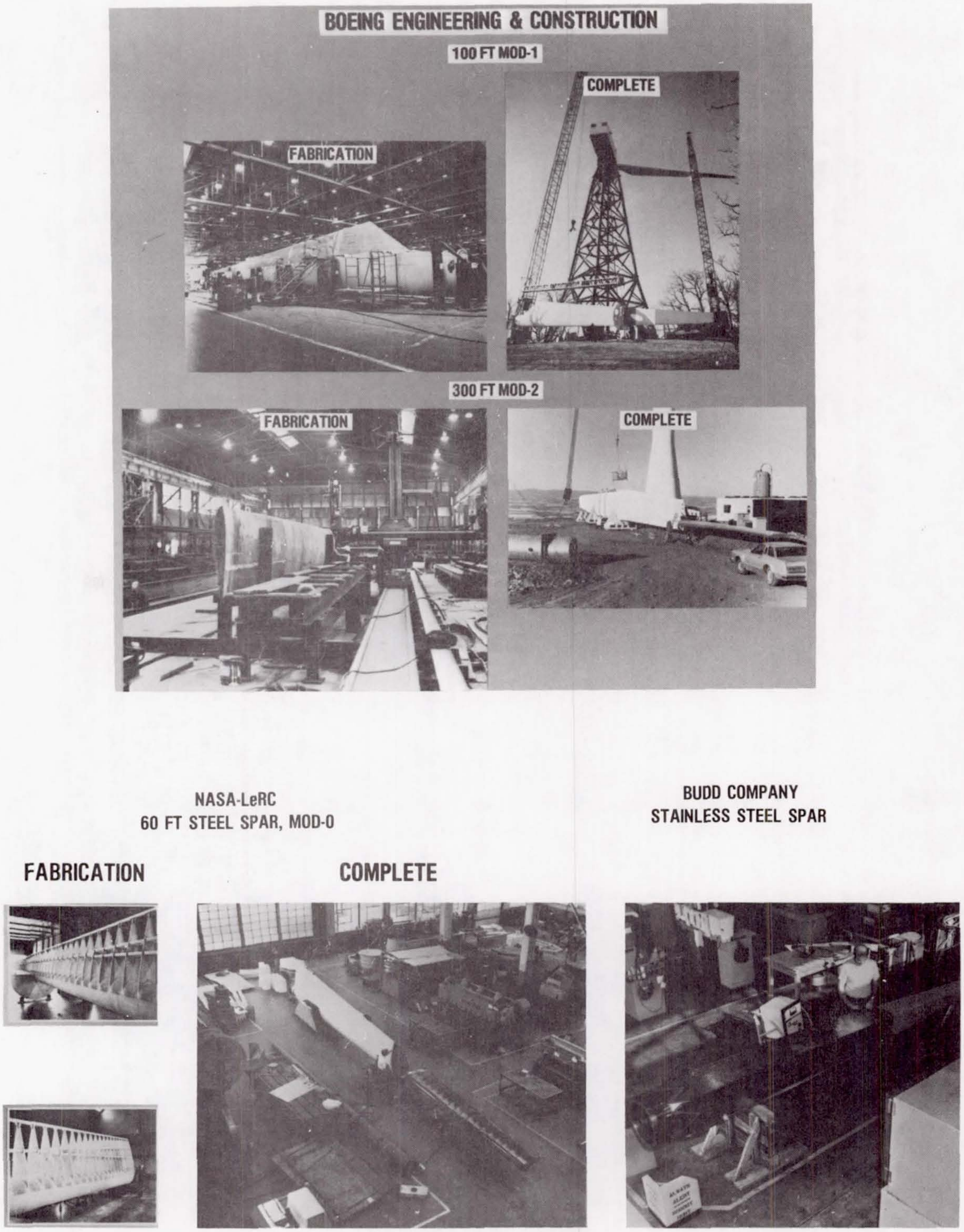


Figure 17. - Mod-0, Mod-1, and Mod-2 steel blades.

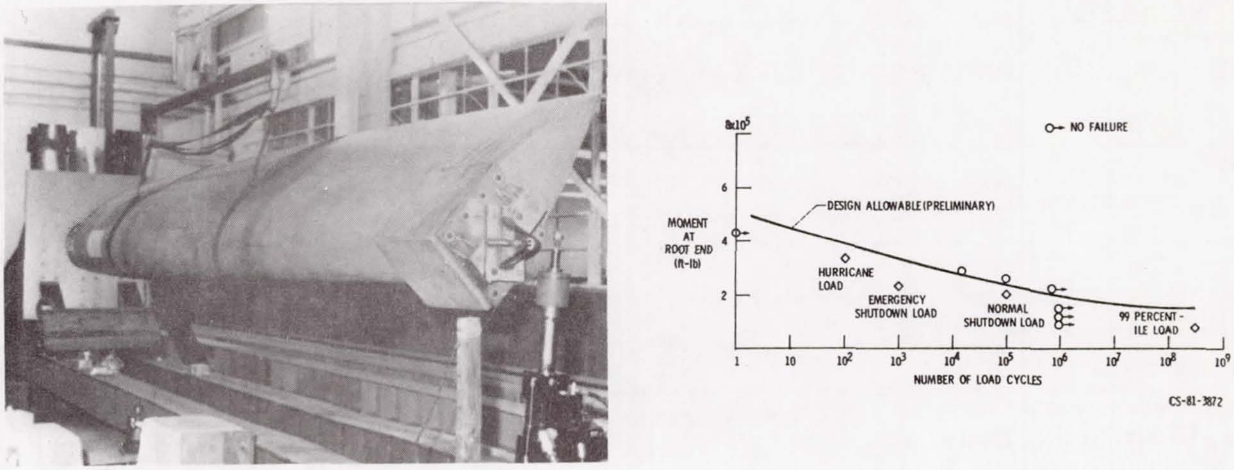
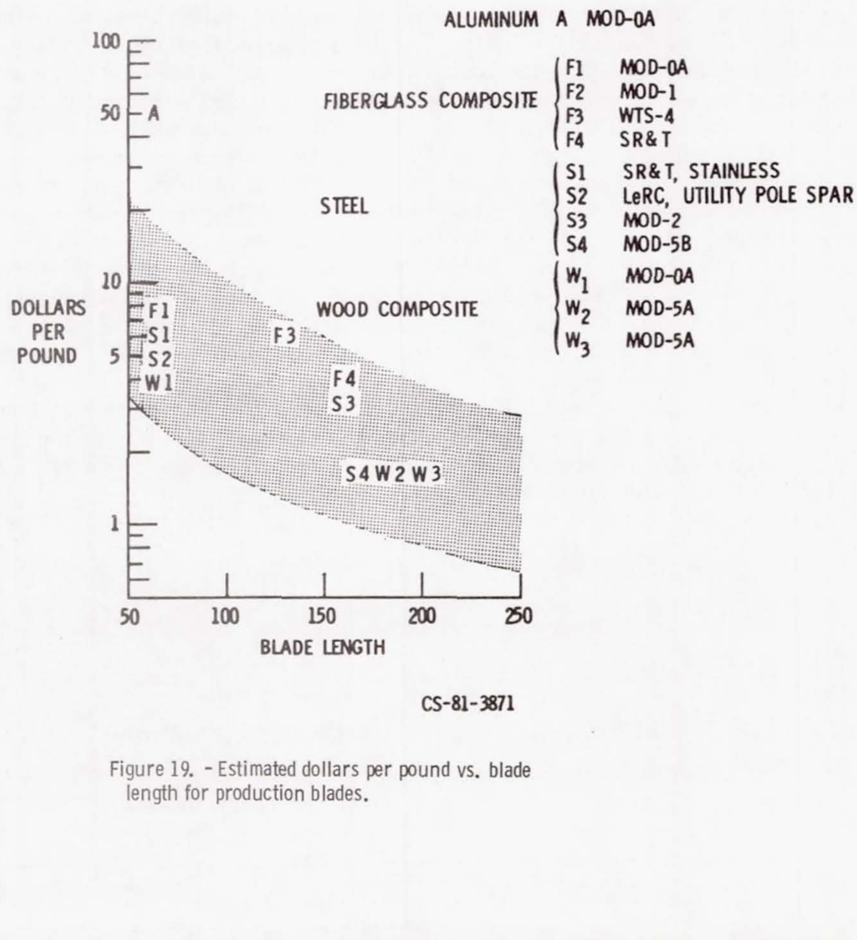


Figure 18. - Blade fatigue testing at Ft. Eustis.



CS-81-3871

Figure 19. - Estimated dollars per pound vs. blade length for production blades.

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
NASA TM-82761		

4. Title and Subtitle	5. Report Date
THE NASA LEWIS LARGE WIND TURBINE PROGRAM	
	6. Performing Organization Code 776-31-41
7. Author(s) R. L. Thomas and D. H. Baldwin	8. Performing Organization Report No. E-1082
	10. Work Unit No.
9. Performing Organization Name and Address National Aeronautics and Space Administration Lewis Research Center Cleveland, Ohio 44135	11. Contract or Grant No.
	13. Type of Report and Period Covered Technical Memorandum
12. Sponsoring Agency Name and Address U.S. Department of Energy Division of Wind Energy Systems Washington, D.C. 20545	14. Sponsoring Agency ~~Code~~ Report No. DOE/NASA/20305-7

15. Supplementary Notes

Prepared under Interagency Agreement DE-AI01-79ET20305. Prepared for Fifth Biennial Wind Energy Conference and Workshop, Washington, D.C., October 5-7, 1981.

16. Abstract

The large wind turbine program is a major segment of the Federal Wind Energy Program sponsored by the Department of Energy (DOE). The NASA Lewis Research Center manages the large wind turbine program for DOE. The large wind turbine program is directed toward development of the technology for safe, reliable, environmentally accpetable large wind turbines that have the potential to generate a significant amount of electricity at costs competitive with conventional electric generation systems. In addition, these large wind turbines must be fully compatible with electric utility operations and interface requirements. There are several ongoing large wind system development projects directed toward meeting the technology requirements for utility applications. First generation technology machines (Mod-0A and Mod-1) and second generation machines (Mod-2) are in operation at selected utility sites. Third generation technology machines (Mod-5) are in the design phase and are scheduled for initial operation in 1984 if project funding is continued. Each successive generation of technology has shown potential to increase reliability and energy capture, while reducing the cost-of-electricity. These advances are being made by gaining a better understanding of the system design drivers, improvements in the analytical design tools, verification of design methods with operating field data, and the incorporation of new technology and innovative designs. This paper provides an overview of the large wind turbine program activities managed by NASA Lewis. These activities include results from the first and second generation field machines (Mod-0A, -1, and -2), the design phase of the third generation wind turbine (Mod-5) and the advanced technology projects. Also included is the status of the Department of Interior WTS-4 machine for which NASA is responsible for technical management.

17. Key Words (Suggested by Author(s))	18. Distribution Statement
Wind energy; Windmills; Wind turbines; Renewable energy; Solar energy	Unclassified - unlimited STAR Category 44 DOE Category UC-60

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price*
Unclassified	Unclassified		

* For sale by the National Technical Information Service, Springfield, Virginia 22161